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Traditional fire use impact in the aboveground carbon stock of the chestnut forests of Central Spain and its implications for prescribed burning

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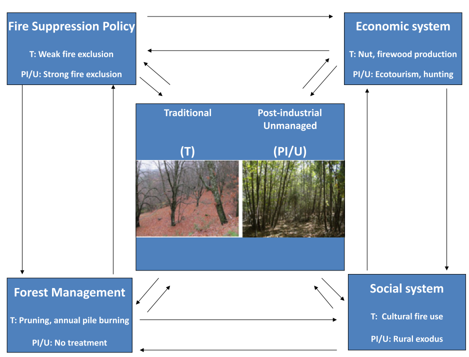
HIGHLIGHTS

- Traditional cultural fire use is essential for the conservation of chestnut forest ecosystems
- Traditionally managed chestnut forest stands accumulate on average 2.6 times more carbon than unmanaged sites
- Traditionally managed chestnut forest stands present 4.4 times more understory species that unmanaged sites
- Due to land use changes, fire exclusion policies and rural demographic trends traditional fire use is declining.
- Surrogate prescribed burning plans based on traditional fire use should be developed to offset this decline.

GRAPHICAL ABSTRACT



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ABSTRACT

Chestnut forest ecosystems have a complex fire ecology; a result of centuries of co-evolution with pre-industrial era, cultural fire use by local communities based on Traditional Ecological Knowledge (TEK). As the "forest transition" unfolds throughout Europe however, and the traditional role of chestnut forest ecosystems as producers of edible nuts and firewood declines, chestnut forest resilience may be endangered due to disturbance regime changes driven by transformations in land use linked to the rural exodus, state fire exclusion policies and climate change. In this study we compared the aboveground carbon stocks of two chestnut forests located in Central Spain which can be considered representative of divergent Europe-wide management trends. In the first site of Casillas traditional understory burning is still widespread and its impacts on forest stand structure can be characterized as maintaining "open canopy", low density stands dominated by old growth chestnut trees. In the second site of Rozas de Puerto Real traditional fire use has declined and natural ecological succession processes have resumed resulting in high density, "closed canopy" stands dominated by young chestnut tree saplings and increasing pine, oak and shrub encroachment. For both sites we used in-the-field monitoring methods to estimate aerial carbon stock using allometric equations. Our results suggest that carbon sequestration and species richness is greater in the traditionally managed chestnut forest stands. Since present demographic trends present difficulties for the maintenance of traditional fire use by local communities, we argue that future fire management of

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unmanaged chestnut stands and maintenance of traditional forest stands ought to be implemented through surrogate prescribed burning plans that replicate the seasonal timing and ecological effects of TEK based controlled burning.

1. Introduction

The Forest Transition Model (FTM) theorizes that forest cover tends to expand as societies undergo industrialization and urban development (Mather, 1992). This expectation arises from the untested hypothesis that as rural population density declines forests expand and biomass per hectare and carbon uptake should also necessarily increase (Mather, 1992; Mather and Needle, 1998; Walker, 1993; Houghton et al., 2000; Rudel et al., 2005; Angelsen and Rudel, 2013). On the basis of the conventional wisdom generated by theories such as FTM, policy networks linked to European climate change mitigation efforts have sought to incentivize reforestation and afforestation policies. These policies have become firmly established as one of the key "low cost" strategies in the global climate change mitigation regime for the foreseeable future though empirical evidence supporting the FTM has been obtained from only a few European and Asian experiences (Rudel et al., 2005; Stern, 2007; Barbier et al., 2008; Angelsen and Rudel, 2013). European countries, in particular, experienced substantial expansions in forest cover as they industrialized and urbanized thus seemingly corroborating the main tenets of the FTM (Fuchs et al., 2014; European Environmental Agency, 2015). Though, there is no doubt that the FTM provides valuable insights into the relationship between large-scale socio-economic development processes and forest cover trends it also seems to show some limitations regarding the potential increases in carbon sequestration to be derived from net expansions in forest cover (Oliveira et al., 2017). These limitations are often related to the omission of the role played by fire as a disturbance regime in many of the Earth's terrestrial ecosystems (Chapin et al., 2000; Hurteau et al., 2008; Oliveira et al., 2017). Some studies, in fact, have begun to empirically test the hypothesis that as forest cover expands so does the frequency and intensity of fires which may result in unintended positive feedback loops with climate change, increased landscape fuels and state led fire exclusion policies (Seijo and Gray, 2012; Stephens et al., 2014). These changing feedbacks could potentially contribute to an increase in greenhouse gas emissions from the forestry sector in spite of net expansions in forest cover (Chapin et al., 2008; Hurteau et al., 2008; Batllori et al., 2013; Stephens et al., 2014; Oliveira et al., 2017).

Chestnut forests in Spain, and by extension Europe, are currently experiencing a forest transition (Conedera et al., 2016). During the 20th century many chestnut forests were abandoned as a result of the gradual decline of pre-industrial forms of land use and management that require continued cultural, labour intensive inputs (Grund et al., 2005; Krebs et al., 2012; Pezzatti et al., 2013; San Roman et al., 2013; Zlatanov et al., 2013; Seijo et al., 2015, 2017; Conedera et al., 2016). Chestnut forest cover however, as the FTM predicted, expanded overall, though old growth formations are increasingly encroached upon by younger saplings from both chestnut and other deciduous and conifer tree species growing in dense, closed canopy formations as natural ecological succession processes resume (San Roman et al., 2013; Zlatanov et al., 2013; Conedera et al., 2016; Seijo et al., 2017). As a result researchers and managers have become concerned with the continued ability of chestnut forest ecosystems to provide valuable ecosystem services, such as the conservation of biodiversity and carbon sequestration, under the new circumstances generated by the rural exodus, land use transformations, climate change and changing fire regimes (Pezzatti et al., 2013; San Roman et al., 2013; Seijo et al., 2017).

Much of this uncertainty centers around the potential resilience, or lack thereof, of chestnut forest ecosystems to changing disturbance regimes, especially fire (Zlatanov et al., 2013; Conedera et al., 2016; Seijo et al., 2017; López-Sáez et al., 2017). Like many other Mediterranean species, chestnuts have a complex fire ecology often linked to annual, low intensity, non-vegetative season, anthropogenic traditional fire use (Grove and Rackham, 2000; Pausas and Keeley, 2009; Seijo et al., 2015, 2017; López-Sáez et al., 2017). These pre-industrial era forms of cultural burning based on Traditional Ecological Knowledge maximizing the exploitation of food products and firewood, may have in fact augmented chestnut tree resilience to fungal and insect pests while modifying some key fire regime attributes that, in turn, may have helped prevent large fires and conflagrations by reducing landscape fuel beds and ladder fuels (Seijo et al., 2015, 2017).

The half a century long application of state policies of fire exclusion, climate change and recent transformations in land use may however lead to important fire regime transformations in Mediterranean type ecosystems where fire events may be getting larger and more severe (Moreira et al., 2011; Fernandes et al., 2013; Stephens et al., 2014; Oliveira et al., 2017). Studies based on the evolution of land use and land cover trends during the last 20th century have confirmed that traditional activities (i.e. agriculture and animal husbandry) were abandoned in Mediterranean rural areas when they were depopulated (Grove and Rackham, 2000; Viedma et al., 2006, 2016; Moreira et al., 2011). These socioeconomic changes along with the expansion of wildland-urban interface areas and the aforementioned factors may be accentuating the coupling of fire regimes with climate (Pausas and Fernández-Muñoz, 2012). These general fire regime trends could have important consequences for the ability of chestnut forest ecosystems to continue sequestering carbon and provide other key ecosystem services in the near future in spite of their relatively recent net expansion.

In this article we will explore these hypotheses about the chestnut forest transition through the empirical evidence obtained from one such process taking place in two chestnut forest ecosystem sites in Central Spain that can be considered representative of Europe-wide trends (Conedera et al., 2016). Specifically we compared carbon aboveground vegetation stocks and species richness in two contrasting chestnut forest ecosystem with diverging fire regimes and management strategies associated with human systems exhibiting markedly different levels of economic development (Seijo and Gray, 2012). We make the case that our findings can inform and offer valuable insights into the unintended ecological consequences of the FTM in terms of carbon balance, species richness and, indirectly, fire risk. These insights could in turn provide useful social-ecological criteria for the formulation of climate change mitigation and adaptation strategies that take into consideration the potential use of prescribed burning inspired by traditional fire use to help abate landscape fuels while simultaneously favouring chestnut forest ecosystem resilience to fire and insect disturbances, conserving biodiversity and enhancing local rural economies through high added value nut production (Seijo et al., 2015, 2017).

2. Methods

2.1. Study area, site characteristics and fire regimes

This study was conducted in sweet chestnut (*Castanea sativa* Mill.) forest stand sites of Casillas and Rozas located in the foothills of the mountains of Gredos (Central Spain) (Fig. 1). Data collection was carried out at 900–1100 m·a.s.l. range of elevation hillside forests, with south-southeast orientation and the same slope ranges in Casillas (40°19′N

and 4°34′W), autonomous community of Castilla y León, and on the limit between Navahondilla and Rozas de Puerto Real (40°18′N and 4°29′W) autonomous community of Madrid in the summer of 2016. These municipalities are contiguous geographically but separated by a political boundary between autonomous communities in the Spanish state and exhibit contrasting forest and fire management strategies. Site selection was determined theoretically by previous studies (Seijo et al., 2015, 2017) based in the contrasted economic development levels of both municipalities and, especially, the forest stand structure that represented the different forest and management strategies applied during the last century (late 1800s in the less developed site of Casillas and 1986 in the more developed site of Rozas de Puerto Real – from now on referred to as Rozas) as well as the uneven intensity of implementation of autonomous community fire exclusion policies (Seijo et al., 2015, 2017).

Based on these previous studies´ findings, we selected for analysis “traditional” stands (defined as open canopy, old growth, clear understory chestnut forest stands for nut production maintained through annual literfall pile burning by local communities) located in Casillas, whose stand structure resembles those of “dehesas” or Mediterranean savannas (grassland or scrubland communities, associated with big diameter, old growth scattered trees). In contrast, in Rozas, our selected stands were characterized as being “unmanaged” since the forest structure was dominated by very dense closed canopy chestnut groves, composed of young trees re-sprouting from root systems and associated coppiced chestnut stands. In these “post-industrial” era chestnut forest stands natural forest succession processes have resumed either due to a lack of active management or to foster the creation of hunting real estates and ecotourism developments where “wilder” looking chestnut forest stands are preferred (Geist et al., 2001; Council of Europe, 2007).

Despite differing significantly in economic development levels and state fire exclusion investments and policy implementation, the municipalities share, as noted, similarities in their biophysical conditions. The potential vegetation of the area corresponds to the *Luzulo-Quercetum pyrenaicae* series (Rivas-Martinez, 1987). The soils are of granitic origin, and can be classified as humid brown soils (humic cambisols according to the FAO nomenclature, FAO, 1981) that can contain an important amount of humus. Both sites are characterized by a dry-summer Mediterranean climate, with precipitation concentrated in the autumn, spring and winter months. Mean annual temperature for Rozas is 12.1 °C and 13.4 °C for Casillas, and mean annual precipitation is 831 mm in Rozas and 978 mm in Casillas based on data from meteorological stations located in each village (Seijo et al., 2015).

Local communities in the less economically developed site of Casillas still carry out TEK based traditional fire use practices in order to promote an open canopy, old growth chestnut forest stand structure. In this site state authorities, for a variety of reasons, have applied fire exclusion policies with less intensity than in the adjacent more developed site of Rozas (Seijo and Gray, 2012; Seijo et al., 2015, 2017). In the more economically developed site of Rozas traditional fire use has, consequently, practically disappeared. Additionally, state fire exclusion policies are applied with more intensity in Rozas due to the autonomous community of Madrid's greater financial resources (Seijo et al., 2015). Chestnut forest use has also shifted away from traditional, pre-industrial era nut and firewood production to emphasize eco-tourism and recreational hunting estate activities which are based on “wilder”, unmanaged landscape aesthetic preferences (Council of Europe,

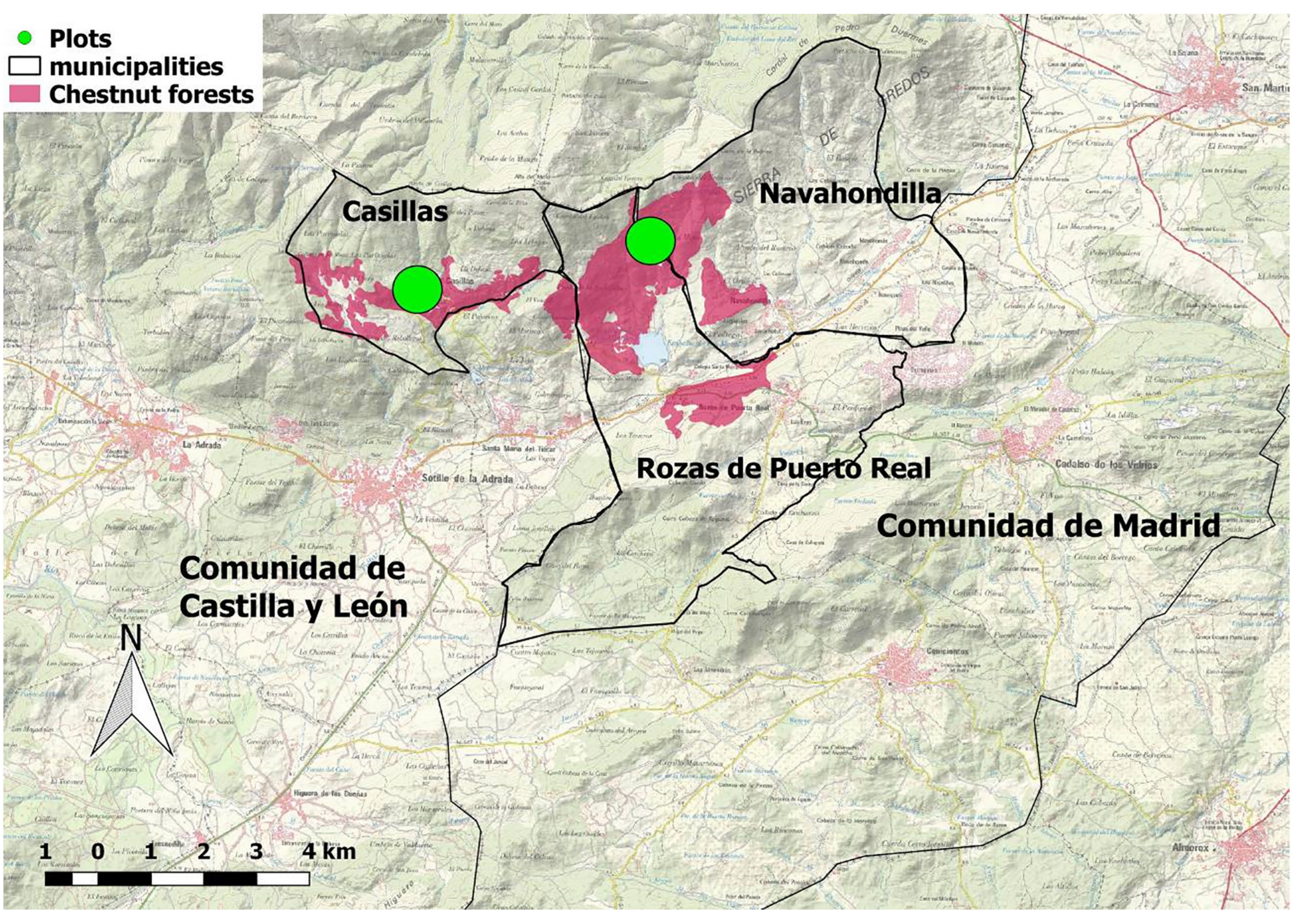

Fig. 1. Map indicating the location of the study sites in Central Spain - Casillas and Rozas - within the Iberian Peninsula. Red color indicates chestnut forest extent, green dots the sampled plots for each management strategy and black lines boundaries between municipalities and autonomous communities.

2007). Previous studies have shown that changes in vegetation, fuel continuity and forest stand structure at the landscape level associated with these latter management goals may be associated with changes in fire regime attributes for both sites. In these studies divergent fire regimes were characterized for the traditionally managed and "unmanaged" chestnut forest stands of Casillas and Rozas respectively (Seijo et al., 2015, 2017; Viedma et al., 2006). Wildfire event incidence as recorded in official autonomous community records was greater in Casillas than in Rozas from 1984 to 2009 with the former experiencing 52 fire incidents in contrast to 31 in the latter. Median annual burned areas per fire event were similar for both municipalities (Rozas 0.41 ha, Casillas 0.42 ha) but once differences in landscape area were accounted for, burnt surface per year was larger in Rozas than in Casillas by a factor of 10 (2.12 ha km^2 $yr.^{-1}$ compared to 0.22 ha km^2 $yr.^{-1}$). These remarkable fire regime differences seem to be mainly driven by the large fire Rozas experienced in 1985 (1257 ha: i.e. official statistical definition in Spain: >500 ha) whereas none of these events took place in Casillas during the recorded period. The plots we sampled in Rozas were all, in fact, affected by this large fire which in turn has decisively affected present stand structure. In Casillas fire incidents in early spring and autumn months account for a much greater proportion (53%) than summer fires (47%). This contrasts with Rozas where summer months account for the vast majority of fire events (71%) with early spring and autumn months fire events amounting to far less (29%). Finally, according to a pilot fire history study carried out in both locations, more fire events appear in fire scarred chestnut trees in Rozas than in Casillas (Seijo et al., 2017). These findings suggest that fire severity could possibly be greater, in spite of less fire incidence, in Rozas than in Casillas but more studies would be needed to further ascertain this hypothesis (Table 1).

2.2. Studied species

The sweet chestnut (*Castanea sativa* Mill.) is a deciduous, hard-wood angiosperm tree species native to Western Europe and the Iberian Peninsula, where several pre-Holocene glacial refugia have been identified (López-Sáez et al., 2017). It has been widely cultivated throughout the Mediterranean Basin, in areas with abundant precipitation and its geographical range is closely associated with the activities of pre-industrial traditional agrarian societies and their targeted products and services (Conedera et al., 2004; López-Sáez et al., 2017). Recent studies in the area (Prada et al., 2016) have pointed to the importance of improving the management and economic potential of sweet chestnut, and also, called for the quantification of its role in mitigating climate change through its storage of carbon in long and medium-term products.

We complementarily used data obtained by Seijo et al. (2015, 2017) for chestnut forest management types and their impact on fire regime changes and stand structure in the Gredos mountain range of Central Spain. These studies revealed connections between economic and political development processes and forest stand structure in these ecosystems that is not only relevant to this specific study area but is also emblematic of current chestnut forest transitions taking place throughout all of Europe (Grund et al., 2005; Krebs et al., 2012; Pezzatti et al., 2013; San Roman et al., 2013; Zlatanov et al., 2013; Seijo et al., 2015, 2017; Conedera et al., 2016).

2.3. Sampling design

In the summer of 2016 we sampled monospecific chestnut forest stand structures shaped by the different management strategies applied to them (therefore referred to as traditional and unmanaged) in two different unevenly developed municipalities; Casillas and Rozas (Fig. 1).

At each of the two sites, efforts were made to derive biometric estimates of total carbon storage in the aboveground vegetation as one of the most important carbon retention pools, and to compare the effects of the different forest stand structures derived from alternative management strategies associated with different economic development levels as identified in previous chestnut forest ecosystem studies in both sites (Seijo et al., 2015, 2017). For each site, 3 circular plots (15 m radius) were established, their GPS coordinates registered for the plot center and, within them, individual tree variables were obtained for the biomass study. We estimated the richness of species in the understory for each management strategy by counting the established species in the sampling plots.

Within each plot, we measured the perimeters at breast height (1.3 m) of all trees with a diameter >5 cm using a measuring tape. We then reconstructed the average forest structure following the Spanish National Inventory's diametric classes (5 cm range diametric classes) so as to determine tree density per hectare. The heights of all trees were measured by combining the angular measurements from a clinometer and the distance to the plot center measured with a laser telemeter, when this was feasible. Since the high density of the stands in the Rozas plots rendered the viewing of the canopy crown and even the crown base height impossible, heights were finally estimated using LiDAR data. The LiDAR data were downloaded from the National Airborne Orthophotography Plan (PNOA), hosted and performed by the National Geographic Institute, Ministry of Infrastructure of the Spanish Government. The LiDAR cloud data from the PNOA have a point density

Table 1
Divergent fire regime attributes in Casillas and Rozas de Puerto Real and matching chestnut forest stand structure 1984–2009.

Fire management	Fire incidents	Severity	Season	Burnt Surface	Stand structure
Traditional fire use	52	Low severity	53% non-vegetative	0.22 HA KM2YR-1 No large fire events (>500 ha)	
Post-industrial unmanaged	31	Medium severity	71% vegetative	2.12 HA KM2YR-1 Large fire event 1985 1267 ha	

of 0.5 first return per square meter, enough to derive the dominant height for homogenous forests such as the ones studied here. In order to assure the comparability of the two sets of plots, the tree heights were derived from the LiDAR data processing for both sets. From the normalized tree heights, that is, the difference between the crown top's elevation and the ground elevation, the 95th percentile was used as the most reliable value for tree heights for each spot.

2.4. Total aboveground biomass and carbon storage

The application of mathematical allometric equations has been widely used in forest biomass estimates to assist managers with decision making and policy development. The estimation of aboveground biomass weight provides a suitable management tool for use by forest managers and researchers (carbon cycle studies, nutritional balances of the forest system, etc.) at different scales (e.g. individual tree or stand level). In spite of the existence of these non-destructive methodologies, there are only few studies focused on hardwood species in Europe. *Castanea sativa* Mill., and by extension chestnut forests, have been the focus of some studies aimed at the monitoring of biomass, forest productivity, and carbon dynamics under different forest management activities (Leonardi et al., 1996; Montero et al., 2005; Salazar et al., 2010; Ruiz-Peinado et al., 2012; Menéndez-Miguélez et al., 2013; Prada et al., 2016). For this specie, many of the applied nonlinear allometric models allow to calculate values for different plant sections (trunk, branches of different thickness), and also total root and aboveground biomass for each individual tree. Each model has its own specific requirements, but the most common explanatory tree variable correlated with the biomass is the diameter at breast height (dbh). The accuracy of the biomass estimates is usually increased through the inclusion of tree height, and some authors have also considered stand variables (such as age, basal area, site index or dominant or mean height) for improving the accuracy of the estimations (Menéndez-Miguélez et al., 2013). The biometric measures presented in this study were focused specifically on carbon storage in aboveground vegetation and do not include possible carbon stocks present in soils.

We estimated total aboveground biomass by applying five different individual tree allometric equations considering as explanatory variables dbh and, in two cases, LiDAR derived tree height as well (Ruiz-Peinado et al., 2012; Menéndez-Miguélez et al., 2013) depending on the characteristics of each model (Table 2). These equations have been most commonly used in the literature for estimating large scale inventory-based forest carbon biomass budgets across regional boundaries in Southern Europe for chestnut forests (Leonardi et al., 1996). Some of the models have been widely applied in the last 20 years in projects related with biomass accumulation and carbon dynamics as in, for instance, the one employed by the Spanish state's Third Forest National Inventory (Ruiz-Peinado et al., 2012; Montero et al., 2013) carbon budget that served as the base for the "Evaluation Report on Impacts, Vulnerability and Adaptation in the Forests and Biodiversity of Spain in light of Climate Change" (Herrero and Zavala, 2015). In the present study, the total biomass for each plot was measured by summing up all the individual tree aboveground biomass estimates within it. The carbon content was set at 48.4% of the total aboveground biomass estimates (Montero et al., 2005).

The perimeter measured on all trees at breast height (1.3 m) was transformed into diameter at breast height values (dbh, cm) which were then used as a data input for the allometric equations applied together with the LiDAR-derived tree height (m). Of the five allometric models we applied (Table 2), only two use tree height as an explanatory variable for biomass calculation. Total aboveground carbon storage by plot, tree and hectare were also calculated following the five different allometric equations.

2.5. Statistical analysis

It is well-known that carbon estimates can vary considerably depending on the different micro environmental and local characteristics of specific study areas. However, to extrapolate and strengthen our results and expand our conclusions with respect to the management practices, total carbon storage under different management treatments (traditional and unmanaged) were calculated and compared for the two different sampled plots through a straightforward one-way ANOVA analysis. Due to the large amplitude of the values obtained in the biomass estimates, P values were considered statistically significant when $P \leq 0.1$ and displayed in Table 3. Tree density (number of trees per plot) was also statistically compared between the two different management treatments using one-way ANOVA. All statistical analyses were performed with the R statistical software (R Development Core Team, 2008).

3. Results

3.1. Forest structure

A total of 17 trees were measured in the 3 traditional plots (6, 5 and 6 trees per plot respectively) in the Casillas site and 1076 (426, 331 and 319 trees per plot, respectively) in the 3 unmanaged plots of the Rozas site. A completely different forest stand structure for both sites is derived from this data (Fig. 2 and Table 1) resulting from these divergent management strategies. Forest management based on TEK is expressed as a statistically significant lower tree density in the stands ($F_{1,4} = 108.78$, $P = 0.000$) than in the unmanaged plots. In the traditionally managed plots of Casillas we obtained a mean of 80.2 ± 8 trees per ha while in the unmanaged plots of Rozas we measured 5074.1 ± 829 trees per ha. Size diameter classes were also significantly different for both locations. In the Casillas plots, tree diameters ranged from 16 to 159 cm but most of the individual trees were very large. Trees were smaller in the unmanaged plots of Rozas, where the minimum tree diameter observed (although not considered) was 1 cm for the smallest tree, while the biggest tree was only 24 cm in diameter. These differences in forest stand structure promote noticeable changes in the

Table 2
Summary of the allometric equations used for the study, with reference to the authors publishing them, equation formulae, reference C stock value (if available) and study sites of their adjustment (Place): biomass; biomass codes: W_{tot}: total; W_s: stem; W_{th}: thick branches; W_{mb}: medium branches; W_b: thin branches.

Authors	Equations	Ref. C content	Place
Ruiz-Peinado et al. (2012) W_{tot} = stems + thick + medium + thin branches	$W_s = 0.0142 \cdot d^2 \cdot h$ $W_{th} = 0.223 \cdot (d - 12.5)^2$ $W_{mb} = 0.230 \cdot d \cdot h$ $W_b = 0.221 \cdot d \cdot h$	Mean total C: 344.5 (kg/tree)	Central Mountain Range and Sierra de Ronda (Spain)
Menéndez-Miguélez et al. (2013) W_{tot} = wood + bark + crown	$W_{wood} = 0.01391 \cdot (d^2 \cdot h)^{1.006}$ $W_{bark} = 0.004119 \cdot h^{1.086} . (d^2)^{0.7889}$ $W_{crown} = 0.5408 \cdot h^{-1.439} \cdot (d^2)^{1.386}$	–	Asturias (Spain)
Patrício et al. (2004)	$W_{tot} = 0.1236\, d^{2.3929}$	106.85–228.75 (Mg/ha)	Northern Portugal
Montero et al. (2005)	$W_{tot} = e^{-1.70831} \cdot d^{2.21544} \cdot e^{(0.223169\char`^2/2)}$	–	Cáceres and Málaga (Spain)
Leonardi et al. (1996)	$W_{tot} = 0.066 \cdot d^{2.628}$	60 (Mg/ha)	Sierra de Gata (Cáceres, Spain)

Table 3
Analysis of variance (ANOVA) for the two managements.

		Df	Sum Sq	Mean Sq	F value	Pr(>F)	Signif.
Ruiz-Peinado et al. (2012)	Treatment	1	4567	4567	1.384	0.305	
	Residuals	4	13,198	4567			
Menéndez-Miguélez et al. (2013)	Treatment	1	12,971	12,971	4.693	0.0962	*
	Residuals	4	11,056	2764			
Patrício et al. (2005)	Treatment	1	35,051	35,051	6.739	0.0603	*
	Residuals	4	35,051	35,051			
Montero et al. (2005)	Treatment	1	7543	7543	4.007	0.116	
	Residuals	4	7530	7530			
Leonardi et al. (1996)	Treatment	1	142,388	142,388	8.485	0.0436	**
	Residuals	4	67,124	16,781			

Significance coding:
* 0.1.
** 0.05.

crown density that clearly influences the micro environmental conditions and the presence of other species in the understory. Thus, the maximum richness of species registered in the open traditional forest plots amounted to 35 different species (mainly herbaceous), while <8 species appeared in the closed canopy unmanaged plots. LIDAR height estimation varied between 17 m and 22 m in Casillas, and 14 m to 26 m in Rozas. However, mean tree height rose to 19.9 m in Casillas and only 15.3 m in Rozas probably due to the tree age differences.

3.2. Carbon storage

Allometric equations resulted in a huge variability of results in terms of aboveground carbon storage in the different plots and trees, depending on the management type (Figs. 3 and 4). Values ranged from a minimum of 81 to 102 Mg/ha and maximum accumulations of 286 to 583 Mg/ha for Rozas and Casillas respectively depending on the allometric model. Carbon storage was higher in the traditional plots of Casillas than in the unmanaged plots of Rozas based on the results of four of the five applied models (significantly higher in three of the four equations), resulting in an average of 2.6 times more carbon stocks in the traditional stands than in the unmanaged ones. Despite the large variability of the biomass estimates among plots subjected to the same forest management strategy, three of the five allometric models applied showed statistically significant higher carbon stocks in the traditional stands of Casillas than in the unmanaged stands of Rozas (Table 3). The equation by Ruiz-Peinado et al. (2012) was the only one that showed an opposite result to the rest of the models, overestimating the accumulation of carbon in unmanaged plots in Rozas and overshooting by more than twice the values obtained with the rest of the models. In addition, this model particularly underestimated the storage capacity of the traditionally managed stands when compared with the other models.

4. Discussion

4.1. Impact of different fire regimes on chestnut forest stand structure in the "traditional" and "unmanaged" plots

Tree density values for the open stands in our study corresponded with the mean tree density values registered for traditional management areas. However, the unmanaged plots in Rozas showed extremely high tree densities in the upper ranges or even exceeding those values registered in the management scenarios described in the specialized literature on the Iberian Peninsula. These densities were even higher than in those stands dedicated to intense, industrial oriented timber production (Prada et al., 2016). Instead, density rates in the unmanaged areas are in the same range as those registered for abandoned chestnut coppice areas in other Mediterranean mountain ranges (Leonardi et al., 1996; Menéndez-Miguélez et al., 2013). As noted by Seijo et al., 2017, differences in forest stand structure translate into significantly different fuel loads and ignition patterns. Similar findings have been obtained in other studies looking at forest stand structure and its influence on fire regime attributes (Agee, 1996; Fernandes, 2009).

The significant differences found in forest structure (tree density and carbon storage per tree) in our study, seem to be closely linked to the diverging fire regime trends in the traditional plots of Casillas and the unmanaged plots in Rozas which experienced a large fire in 1985 (Seijo et al., 2017). Our results seem to replicate, in fact, the findings of Minnich (1983) regarding fire regime divergence between unevenly economically developed Southern and Baja California. It is very likely that divergent fire regimes in Casillas and Rozas are partly driven by the uneven decline of TEK based fire management practices (Seijo et al., 2017). Previous studies have shown that TEK based fire management practices - mainly the non-vegetative season, annual burning of litterfall and ladder fuels – as well as other forms of traditional land

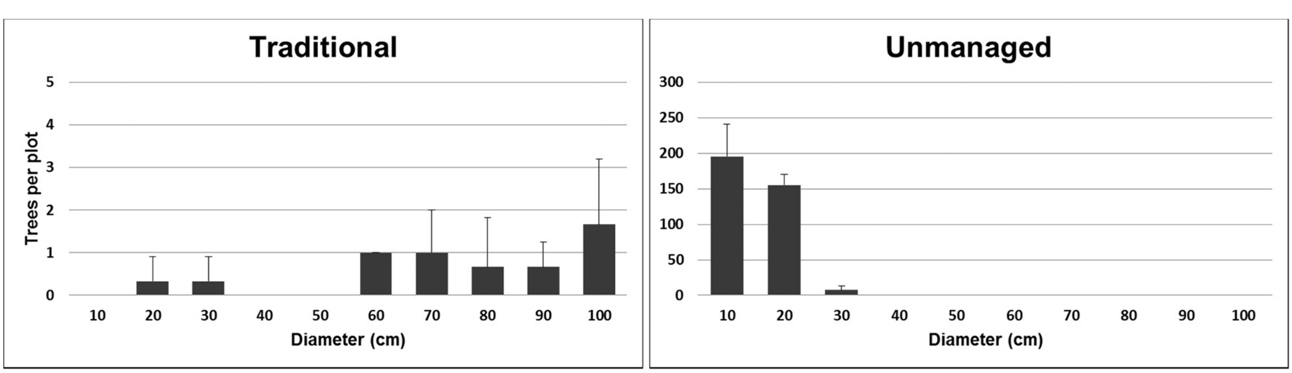

Fig. 2. Mean tree density and distribution of diameter classes of traditional and unmanaged stands in the chestnut forests of Casillas and Rozas respectively. Hanging bars represent standard error.

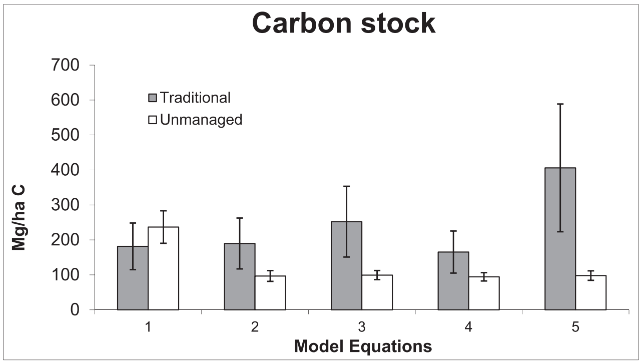

Fig. 3. Average aboveground carbon stock estimates of the plots for the two management types. Error bars indicate standard deviations for each Group, since the value for each plot represents the sum of all trees' biomass. The allometric equations results are: 1. Ruiz-Peinado et al. (2012); 2. Menéndez-Miguélez et al. (2013); 3. Patrício et al. (2005); 4. Montero et al. (2005); 5. Leonardi et al. (1996) Statistical significances from the ANOVA test: 0.1: * and 0.05: **.

use (Viedma et al., 2006) have been steadily declining throughout Gredos though this trend seems to have been more noticeable in Rozas than in Casillas (Seijo et al., 2015, 2017). Official fire statistics (MAPAMA, 2016) indicate that fire incidence is greater in Casillas than in Rozas but burnt surface per incident and in the aggregate is relatively smaller (see Table 1). Wildfire incidents in Casillas seem to be also more closely linked with accidental escapes taking place in the traditional annual pile burning of chestnut leaves and understory fuels during the non-vegetative season, while in Rozas fire incidence increases during the summer, vegetative season months (Seijo et al., 2017).

Seijo et al. (2015, 2017) suggest that traditional chestnut stand fire management practices linked to nut and firewood production based on TEK have influenced considerably the stand structure and fire regime of chestnut forest ecosystems in both municipalities but that, due in all likelihood to the rural exodus and uneven application of fire exclusion policies fires seem to be becoming larger, less frequent and uncharacteristic (i.e. taking place during the vegetative rather than the non-vegetative season as in TEK managed areas) in the unmanaged chestnut forest stands of Rozas (Seijo et al., 2017). Conditions in Rozas, indeed, seem to be shifting towards what Stephens et al. (2014) denominate the "mega-fire" triangle; meaning that antecedent disturbances (the large fire of 1985 in Rozas), the implementation of state fire exclusion policies and climate change could be hypothetically driving the emergence of more infrequent but larger fire events with important ecological and human system consequences (Stephens et al., 2014). This higher "large fire" risk would compound with the lesser efficiency in aboveground carbon storage of unmanaged chestnut forest stands suggesting that traditional, pre-industrial era fire management practices and their impact on stand structure increases carbon stocks while diminishing large fire risk (Table 1).

4.2. Carbon stocks in "traditional" vs. "unmanaged" chestnut forest stands

Although studies on biomass measurement have improved the accuracy of allometric equations for *Castanea sativa* Mill. (Ruiz-Peinado et al., 2012) there still exists an enormous variability in the outcome result for aboveground biomass estimation using the simplest and most accessible independent variable; dbh. In spite of the limitations of some of the applied models (i.e. Ruiz-Peinado et al., 2012 is only applicable with a minimum of 12.cm diameter for thick branches biomass and the maximum diameter used for model construction was 50.6 cm) and of our study due to the lack of a site specific allometric equation to estimate root biomass and other carbon pools (mainly soil carbon stocks) the majority of the models concurred that traditional open stands managed according to TEK criteria accumulated higher amounts of carbon in aboveground vegetation stocks than the unmanaged plots of Rozas. Thus our results suggest that managing chestnut forests with traditional cultivation practices such as grafting and thinning with frequent, low intensity seasonal, litterfall pile burning, increased the total aboveground carbon stock in the vegetation.

Higher tree density in the unmanaged plots of Rozas decreased the amount of carbon storage in the aboveground vegetation compared to the traditionally managed plots, particularly, in the long term if we factor in the increased risk of large fire occurrence (see Table 1). Previous dendroecological studies in the area (Seijo et al., 2017) registered faster annual growth in the unmanaged stands in terms of mean annual tree-ring width (2.8 ± 1.1 mm and 4.3 ± 1.2 mm in traditional and abandoned stands respectively) thus suggesting enhanced carbon accumulation in the short term. Our study suggests, however, that traditional chestnut forest management increases the stable carbon pool in the aboveground vegetation overall and that short term gains in the unmanaged plots are likely offset by temporal and environmental dynamics driven by disturbance regimes such as fires or pests since forests are not infinite, exponentially growing carbon stocks (Prada et al., 2016). Aboveground carbon storage is highly affected by climate, soil composition, forest structure and, of course, management practices (Prada et al., 2016). Tropical forests have the maximum values of carbon storage among the world's biomes. In comparison conifer and oak forests in temperate biomes have a limited yet long-term capacity to store carbon particularly in arid areas such as the Southwest of the United States and the Mediterranean Basin (Ashton et al., 2012).

4.3. Implications for future chestnut forest management: a need for prescribed burning based on TEK based fire practices?

The existing literature on chestnut forest ecosystems suggests that similar natural succession and fire regime dynamics to those observed in Casillas and Rozas are emerging throughout Europe though more case studies would be needed to confirm this hypothesis (Conedera et al., 2016). This study's findings suggest therefore that in locations where TEK-based traditional fire management still exists strategies for adaptation and mitigation to climate change could be conceivably implemented at a minimal economic cost to the state by local communities that have both the TEK and the adequate social, economic and cultural incentives to continue using annual, pile burning of litterfall in chestnut forest landscapes, particularly when taking into account disturbance regime transformations likely to be induced by climate change (Stephens et al., 2014; Seijo et al., 2017).

In fire management it is widely understood that open stands increase solar radiation and wind movement in the understory results in warmer temperatures and drier fuels throughout the fire season. While open stand structures can encourage a surface fire to spread, such fires do little ecological damage if the tree species are adapted to this specific type of historical fire regime (Pausas and Fernández-Muñoz, 2012). These types of frequent, low severity, surface fire events are relatively easy to control and less likely to support a crown fire even under severe weather conditions. However, the vast tree density and closed tree canopy registered in the unmanaged stands of Rozas facilitates the influence of ladder fuels in fire behavior, allowing fires to climb upward into the crowns thus helping to sustain crown fires once they are started (Agee, 1996; Fernandes, 2009). Rapidly moving crown fires typically consume nearly all the fine fuels in a forest canopy when wind and a sloping topography, as in the Gredos mountain range, are thrown into the mix. Nowadays, crown fires caused by excessive fuel accumulation seem to pose a severe threat to ecological and human infrastructure and represent a major challenge for contemporary fire management (Stephens et al., 2014). Despite the variable effects of decreased fire occurrence on fuels and that fire behavior may change subtly from site to site, the higher incidence of crown fires in areas with historically frequent, surface fire regimes is generally occurring all over the world but especially in arid and semiarid areas with

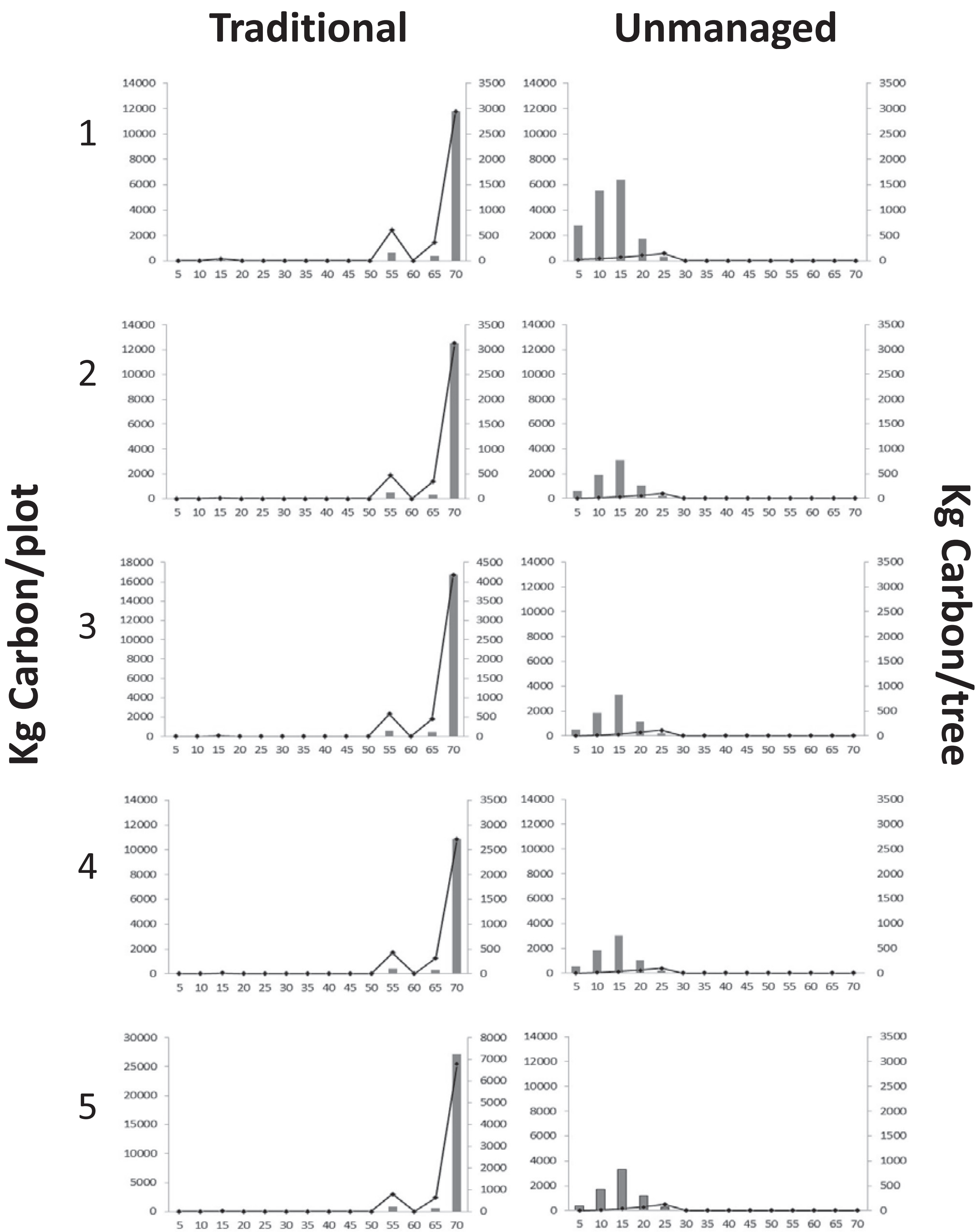

Fig. 4. Average carbon stock estimates in the aboveground vegetation per plot (bars) and per tree (lines) for the two management types per diametric classes (cm). The numbers correspond to the allometric equations models: 1. Ruiz-Peinado et al. (2012); 2. Menéndez-Miguélez et al. (2013); 3. Patrício et al. (2005); 4. Montero et al. (2005); 5. Leonardi et al. (1996).

possibly deleterious ecological and human system consequences (Stephens et al., 2014).

The results of this study suggest that the traditionally managed chestnut forest stands of Casillas sequester carbon more efficiently than the abandoned chestnut forest stands of Rozas in the aboveground vegetation carbon pool. When this evidence is coupled with the greater large fire risk present in the unmanaged plots as well as the lower species richness in their understory some important insights for the future management of these forest ecosystems emerge. If managers find it desirable to maximize carbon sequestration, understory species richness and decrease large fire risk it may be necessary to maintain the annual, non-vegetative season, low intensity, surface fire regime that traditionally managed chestnut forest stands have co-evolved with. Paradoxically, the rural exodus and the ageing of the population in Casillas and Rozas may make this management strategy increasingly difficult to accomplish in the future. Casillas much like many other rural locations throughout Europe exhibits overall population loss and an inverted demographic pyramid (Seijo et al., 2017). Given that much of the TEK based burning is carried out by the older members of the community this does not bode well for their continuity.

Prescribed burning by trained professionals replicating the ecological and human system goals of TEK based burning may therefore constitute one of the few alternatives under the new climate change conditions in the Mediterranean of modulating carbon assimilation and maintaining ecosystem productivity and biodiversity in the "new normal" characterized by more frequent droughts, decreasing precipitation and higher average temperatures (Nemani et al., 2003; Batllori et al., 2013; Fernandes et al., 2013; Khabarov et al., 2016; Vicente-Serrano et al., 2014). The use of prescribed fire should probably be implemented by, or under the guidance of professionals, since current conditions (fuel buildup as the rural exodus proceeds) usually present a high fire escape probability. Nonetheless, mechanical treatments around old growth trees (in combination with prescribed burning in open areas) and thinning in the unmanaged or abandoned plots could conceivably offset these risks. The creation of a Protected Geographical Indication plus an organic certification for chestnuts would also facilitate their sale at a better market price and incentivize continued management by local communities of these forests (Xunta de Galicia, 2017; MAPAMA, 2017). From the large fire risk mitigation point of view, old growth forest stands might represent very interesting stand structures for Strategic Management Points by increasing overall landscape heterogeneity (EFI, 2017). When treating the entire landscape is not feasible; efforts should be focused on specific portions of the landscape where large fire risk can be efficiently reduced. Traditionally managed old growth chestnut forest stands, in sum, may not only represent efficient aboveground carbon stock and biodiversity conservation areas but also interesting wildfire prevention areas already embedded in the landscape.

5. Conclusions

Chestnut forest transitions leading to greater forest cover may, indeed, bolster carbon sequestration but only when and if they effectively take into account important ecological disturbance processes such as fire (Hurteau et al., 2008, 2014; Batllori et al., 2013). In an effort to augment economic productivity and design mitigation policies for greenhouse gases (GHG) emissions through reforestation and afforestation, state foresters, donors and the modern timber industry promote younger and densely wooded forest structures - for hunting estates, logging or recreational eco-tourism purposes - though multiple harvesting options and alternative management strategies exist to harmonize all of these alternative forms of land use (Angelsen and Rudel, 2013; Prada et al., 2016).

Chestnut forests in Rozas are an example of these current forestry practices. By directly or indirectly fomenting denser chestnut forests populated with younger, smaller diameter trees, carbon uptake may be incentivized in the short to medium term harvesting length periods (Álvarez et al., 2014; Prada et al., 2016). However, in the medium to long term the traditionally managed chestnut forests of Casillas are more effective in performing this function given their greater resilience to disturbances such as fires, pests and drought as well as the added value of their greater biodiversity which may also indirectly bolster ecosystem resilience through as yet poorly understood ecosystem feedback mechanisms (Chapin et al., 2000; Oliver et al., 2015). This could have significant implications for forest management of chestnut forest ecosystems throughout Europe which are currently subject to strict state fire exclusion policies and are being allowed to re-wild in part due to the propagation of economic incentives linked to European and global scale climate change mitigation initiatives (Stern, 2007; European Commission, 2011).

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